Final Report for Period: 09/2010 - 08/2011
Submitted on: 12/05/2011
Principal Investigator: Dellaert, Frank .
Award ID: 0713134
Organization: Georgia Tech Research Corp
Submitted By:
Dellaert, Frank - Principal Investigator
Title:
RI: Collaborative Research: Bion-Inspired Navigation

Project Participants

Senior Personnel

Name: Dellaert, Frank
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Gill, Tarandeep
Worked for more than 160 Hours: Yes
Contribution to Project:

Post-doc

Graduate Student

Name: Ranganathan, Ananth
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Fathi, Alireza
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Roberts, Richard
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Beall, Chris
Worked for more than 160 Hours: Yes
Contribution to Project:
Supported with GRA money from ward, worked on stereo-visual odometry

Name: Ta Huynh, Duy-Nguyen
Worked for more than 160 Hours: Yes
Contribution to Project:
Duy was hired as a graduate research assistant over the 2011 Summer semester.

Name: Jian, Yong-Dian
Worked for more than 160 Hours: Yes
Contribution to Project:
Yong Dian was hired in the Fall of 2011 as a graduate research assistant (GRA).

Undergraduate Student

Name: Mei, Henry

Worked for more than 160 Hours: No

Contribution to Project:

Henry, and undergraduate student, provided some support over the summer to help with setting up robot experiments.

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

University of Pennsylvania

Other Collaborators or Contacts

Pablo Fernandez, University of Alcala, was a visitor in the lab for 6 months and collaborated on some visual odometry methods. Several undergraduate students were involved as well.

The PI and Chris Beall engaged in a collaboration with Ian Mahon and Stefan B. Williams from the Australian Centre for Field Robotics at The University of Sydney. They provided us with underwater imagery collected using the Autonomous Underwater Vehicle Sirius, at the South Scott Reef, which is located 300 km northwest of Cape Leveque, Western Australia. This collaboration yielded in a paper that was presented at Oceans 2011, in Santander, Spain.

In Spring 2010 we collaborated with the Georgia Tech Research Institute, Georgia Tech?s contract research arm, on implementing some of the algorithms on an aerial vehicle. In addition, we collaborated with Eric Johnson and Michael Sobers of the aerospace department at Georgia Tech to implement a view-based SLAM method on another aerial vehicle.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

Please see attached file

Findings: (See PDF version submitted by PI at the end of the report)

Please see attached file

Training and Development:

Tarandeep Gill gained significant experience in doing research in the context of a research group, and has chosen to do a master's thesis under the guidance of the PI on the same topic
of random projection methods.

Richard Roberts and Alireza Fathi are being trained as graduate researchers by the PI.

Chris Beall and Yong-Dian Jian were added as GRAs and are being trained as graduate researcher by the PI.

Outreach Activities:

Several students on the award have presented their work in a large poster session highlighting the research in the Center for Robotics and Intelligent Machines at Georgia tech (RIM@GT).

In addition, every year the RIM center, as part of the National Robotics Week, hosts an open house for high-school students from across the state/city.Typically we have 100+ students signed up for the tours, accompanied by their science teachers. As RIM faculty, we believe this is an important to make people aware of our research and to recruit people to STEM fields.

Journal Publications

Ranganathan, A; Dellaert, F, "Online probabilistic topological mapping", INTERNATIONAL JOURNAL OF ROBOTICS RESEARCH, p. 755, vol. 30, (2011). Published, 10.1177/027836491039328

Books or Other One-time Publications

Web/Internet Site

Other Specific Products

Product Type:

PhD Dissertation

Product Description:

Probabilistic Topological Maps.
Ananth Ranganathan
PhD Dissertation, College of Computing
Georgia Institute of Technology, Feb 2008

Sharing Information:

Online

Product Type:

Conference Paper

Product Description:

Bundle adjustment in large-scale 3D reconstructions based on underwater robotic surveys, Chris Beall, and Frank Dellaert, and Ian Mahon Stephen Williams, Oceans '11, 2011

Sharing Information:

Presented at Oceans 2011, in Santander, Spain.

Contributions

Contributions within Discipline:

The Probabilistic Topological Mapping framework is the first instance of a probabilistic technique for topological mapping that is systematic and comprehensive. It is especially relevant for future robotic applications which will need a sparse representation capable of accommodating higher level semantic knowledge. Results from experiments in real environments demonstrate that the framework can accommodate diverse sensors such as camera rigs and laser scanners in addition to odometry.

We introduced the estimation of dense optical flow and ego-motion in a generalized imaging system in an environment that has some degree of statistical regularity. For example, in autonomous ground vehicles the structure of the environment around the vehicle is far from arbitrary, and the depth at each pixel is often approximately constant. We extended the well-known subspace constraints to a very general class of imaging systems, including catadioptric and multiple-view systems. We demonstrated results of finding the optical flow subspaces and employing them to estimate dense flow and to recover camera motion for a variety of imaging systems in several different environments.

Contributions to Other Disciplines:

Environmental change is a growing international concern, calling for the regular monitoring, studying and preserving of detailed information about the evolution of underwater ecosystems. Computer vision offers promising technologies to build 3D models of an environment from two-dimensional images. The result of our 3D reconstruction techniques as published in IROS 2010 and Oceans 2011 produce highly accurate sparse 3D reconstruction of underwater structures such as corals, and hence contribute to the oceanographic research community.

Contributions to Human Resource Development:

As mentioned above, Ananth Ranganathan successfully defended his thesis for a panel of experts. He is now working for Honda research in Cambridge, MA, on humanoid robots. Several other GRAs supported under this grant, while now supported from different sources, are close to graduation and are expected to stay in research after they graduate.

Contributions to Resources for Research and Education:

Contributions Beyond Science and Engineering:

Conference Proceedings

Roberts, R;Potthast, C;Dellaert, F, Learning General Optical Flow Subspaces for Egomotion Estimation and Detection of Motion Anomalies, "JUN 20-25, 2009", CVPR: 2009 IEEE CONFERENCE ON COMPUTER VISION AND PATTERN RECOGNITION, VOLS 1-4, : 57-64 2009

Ranganathan, A;Dellaert, F, Bayesian Surprise and Landmark Detection, "MAY 12-17, 2009", ICRA: 2009 IEEE INTERNATIONAL CONFERENCE ON ROBOTICS AND AUTOMATION, VOLS 1-7, : 1240-1246 2009

Mottaghi, R;Kaess, M;Ranganathan, A;Roberts, R;Dellaert, F, Place recognition-based fixed-lag smoothing for environments with unreliable GPS, "MAY 19-23, 2008", 2008 IEEE INTERNATIONAL CONFERENCE ON ROBOTICS AND AUTOMATION, VOLS 1-9, : 1862-1867 2008

Beall, C;Lawrence, BJ;Ila, V;Dellaert, F, 3D Reconstruction of Underwater Structures, "OCT 18-22, 2010", IEEE/RSJ 2010 INTERNATIONAL CONFERENCE ON INTELLIGENT ROBOTS AND SYSTEMS (IROS 2010), : 4418-4423 2010

Alcantarilla, PF;Bergasa, LM;Dellaert, F, Visual Odometry Priors for robust EKF-SLAM, "MAY 03-08, 2010", 2010 IEEE INTERNATIONAL CONFERENCE ON ROBOTICS AND AUTOMATION (ICRA), : 3501-3506 2010

Alcantarilla, PF;Oh, SM;Mariottini, GL;Bergasa, LM;Dellaert, F, Learning Visibility of Landmarks for Vision-Based Localization, "MAY 03-08, 2010", 2010 IEEE INTERNATIONAL CONFERENCE ON ROBOTICS AND AUTOMATION (ICRA), : 4881-4888 2010

Categories for which nothing is reported:

Any Book

Any Web/Internet Site

Contributions: To Any Resources for Research and Education

Contributions: To Any Beyond Science and Engineering

Final Report: Bio-Inspired Navigation

Findings

Academic Year 2007-2008

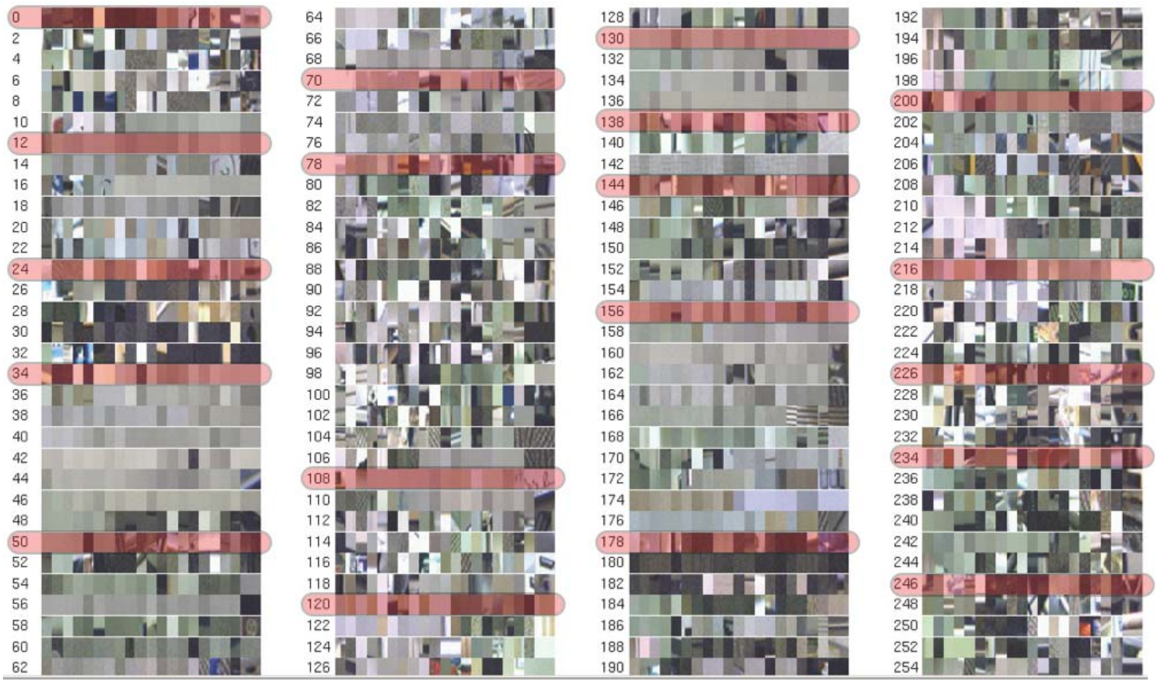


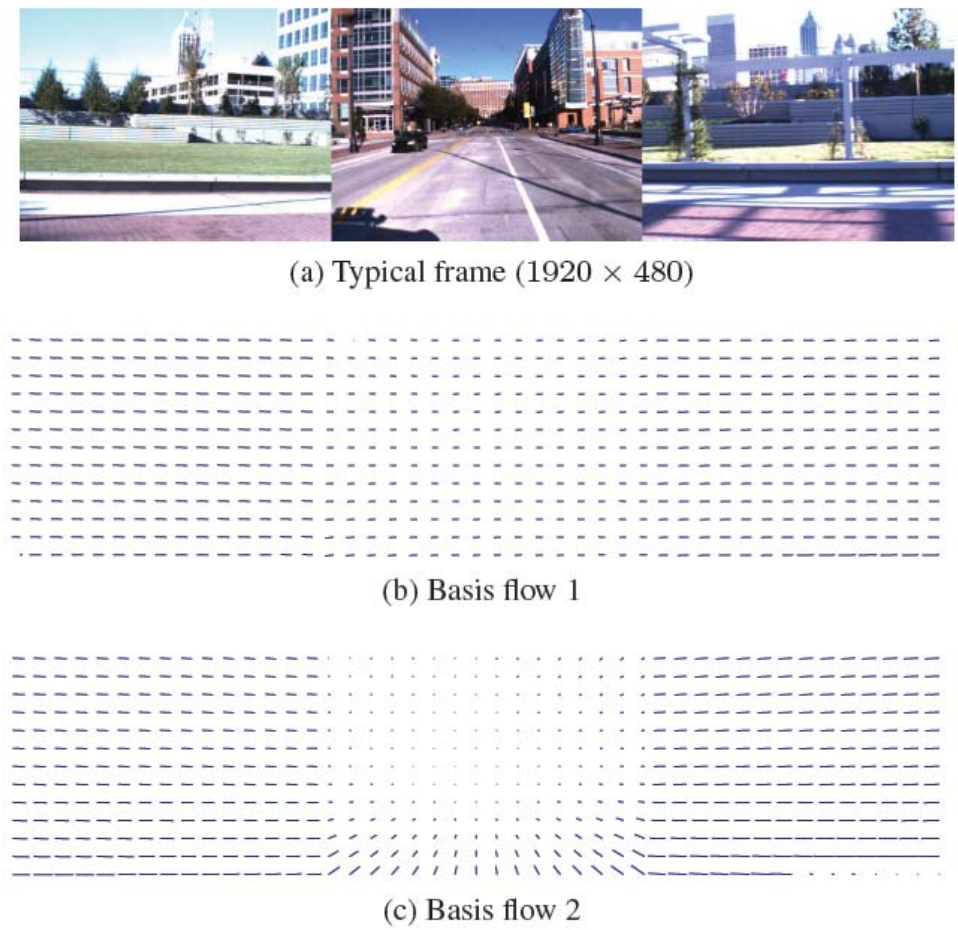
Figure 1: Bayesian Surprise results by Ananth Ranganathan, which was presented at ICRA '09.

To test the notion of Bayesian surprise in the context of probabilistic topological mapping, we implemented and illustrated the computation of surprise for appearance measurements using a bag-of-words model, and using laser range scans, thus proving the generality of the algorithm. These were tested both qualitatively and quantitatively on a number of datasets, hence demonstrating its practicality. We demonstrated that surprise is large when sudden changes in the environment occur, and hence, is a good indicator of landmarks.

An example is shown in Figure 1, which shows the top twenty SIFT features from the appearance histogram for certain places. A total of 19 landmarks were detected in this dataset, and the topology obtained using these landmarks is the same as the ground truth topology. The figures shows the top 20 SIFT feature patches by histogram count from the bag-of-words model for each location denoted by the measurement number for an experiment. The measurements corresponding to landmarks (i.e. where the landmark detector fires) are shown in red (shaded overlay). It can be seen that these correspond to the start of subsequences of measurements that also differ qualitatively from the preceding measurements, for example measurements before 34 are much more cluttered than those following it.

Ananth Ranganathan's PhD dissertation is the culmination of several years of work on PTMs, a probabilistic framework for the construction of topological maps that addresses topological ambiguity, is failure-aware, computationally efficient, and can incorporate information from various sensing modalities. Ananth addressed the two major problems of topological mapping, namely topological ambiguity and landmark detection, through the Bayesian surprise work mentioned above.

Academic Year 2008-2009



(a) Typical frame (1920 × 480)

(b) Basis flow 1

(c) Basis flow 2

Figure 2: Basis flows spanning a two-dimensional linear flow subspace for a 3-camera outdoor driving sequence, captured from an autonomous vehicle (Georgia Tech Sting).

The place recognition work done by **Tarandeep Gill** was found to be very promising. We found that the views defining a place can be very sparse representations indeed, and that random projection methods function better or as good as much more expensive PCA (principal component analysis) based approaches. This work yielded useful insights in the properties of various nearest neighbor schemes in the context of navigation.

The EasySLAM method as investigated by **Alirezha Fathi** has yielded very promising results but more larger-scale experiments needed to be done to truly show off the advantages (scalability, semantic navigation) of the method. Unfortunately, two submissions to robotics conferences were rejected: Alireza was quite discouraged by this and decided to move on to other research interestes (and a different advisor) and hence this promising thread of research did not lead to a satisfactory conclusion. The PI is still interested in this class of techniques, however, and plans to rekindle the work if a student shows interest in the work.

Richard Roberts' basis flow work was very successful and yielded an oral presentation at the 2009 conference on Computer Vision and Pattern Recognition 2009, in Miami, FL. The acceptance rate for oral presentations at this conference was 4%. Richard found that the estimation of dense optical flow and ego-motion in a generalized imaging system can be done by exploiting probabilistic linear subspace constraints on the flow. He dealt with the extended motion of the imaging system through an environment that is assumed to have some degree of statistical regularity. For example, in autonomous ground vehicles the structure of the environment around the vehicle is far from arbitrary, and the depth at each pixel is often approximately constant. The subspace constraints hold not only for perspective cameras, but in fact for a very general class of imaging systems, including catadioptric and multiple-view systems (See Figure 2 for a 3-camera system, taken from Georgia Tech's autonomous vehicle "Sting").

Using minimal assumptions about the imaging system, Richard developed algorithms to learn a probabilistic subspace constraint that captures the statistical regularity of the scene geometry relative to an imaging system. He proposed an extension to probabilistic principal components analysis (PPCA, as first published by Tipping and Bishop, in 1999) as a way to robustly learn this subspace from recorded imagery, and demonstrated its use in conjunction with a sparse optical flow algorithm. To deal with the sparseness of the input flow, we used a generative model to estimate the subspace using only the observed flow measurements.

Additionally, this method can be used to detect outliers in the visual input stream. To identify and cope with image regions that violate subspace constraints, such as moving objects, objects that violate the depth regularity, or gross flow estimation errors, we employed a per-pixel Gaussian mixture outlier process. Richard demonstrated results of finding the optical flow subspaces and employing them to estimate dense flow and to recover camera motion for a variety of imaging systems in several different environments.

Academic Year 2009-2010

In Fall 2009, as discussed above, Richard and the PI started working on "Appearance Manifolds". We showed how this idea can easily be implemented in practice for a specific choice of the mixture components, i.e., the chart-based PPCA mixture model, a generalization of the PPCA mixture model by Tipping and Bishop. We obtained a generative joint probability density model on image measurements and the underlying latent variable from which they arise, specifically for the case where the latent variable lives on a differentiable manifold.

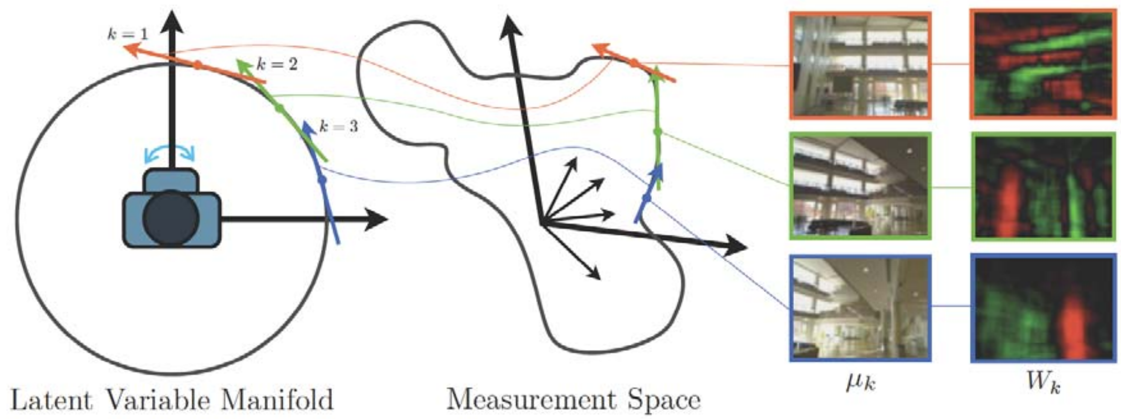


Figure 3: Chart-based PPCA mixture model. The latent variable manifold (left) generates measurements in a higher-dimensional measurement space (middle), for example corresponding to entire images (as shown on the right, with their first derivatives).

A key contribution was that we did not assume that the latent variable manifold is globally isometric to a vector space. That is, there is no natural global coordinate system nor origin for the latent variable manifold. Instead, we exploited the differentiable manifold nature of the latent variable space as encoded in a chart atlas. The idea is illustrated for image-based measurements in Figure 3, above. We showed how this idea can easily be implemented in practice for a specific choice of the mixture components using the chart-based PPCA mixture model. Richard also derived an EM algorithm to learn this coordinate-free manifold model, which has a clear interpretation and leads to efficient inference algorithms.

To test the whole-image appearance-based mobile robot localization, Richard performed experiments with a Segway-based mobile platform, demonstrating the ability to localize on the latent variable manifold using a particle filter, and to synthesize new views from locations not in the training data. Unfortunately, the results were mixed: while localization worked, the accuracy was not as good as desired, and in general we found that the appearance prediction was poor with the chart-based mixture model. While the mathematical idea is sound, we hypothesized that the linear mixture of appearance is simply not a good model for image formation: it does not generalize well far away from the locations where the data was collected. While this is a negative result, we are hopeful that combining appearance and flow (which was very successful in Richard's earlier work) might lead to a more realistic and useful model.

In Spring 2010, Richard found that the optical flow algorithms he previously developed could be implemented in real-time on aerial platforms and lead to successful stabilization of a coaxial helicopter. In addition, view-based SLAM was implemented and demonstrated on simulated data.

Academic Year 2010-2011 (No Cost Extension)

Computer vision offers promising technologies to build 3D models of an environment from two-dimensional images. Environmental change is a growing international concern, calling for the regular monitoring, studying and preserving of detailed information about the evolution of underwater ecosystems. For example, fragile coral reefs are exposed to various sources of hazards and potential destruction, and need close observation. The state of the art techniques have enabled high-quality digital reconstruction of large-scale structures, e.g., buildings and urban environments, but only sparse representations or dense reconstruction of small objects have been obtained from underwater video and still imagery. The application of standard 3D reconstruction methods to challenging underwater environments typically produces unsatisfactory results.

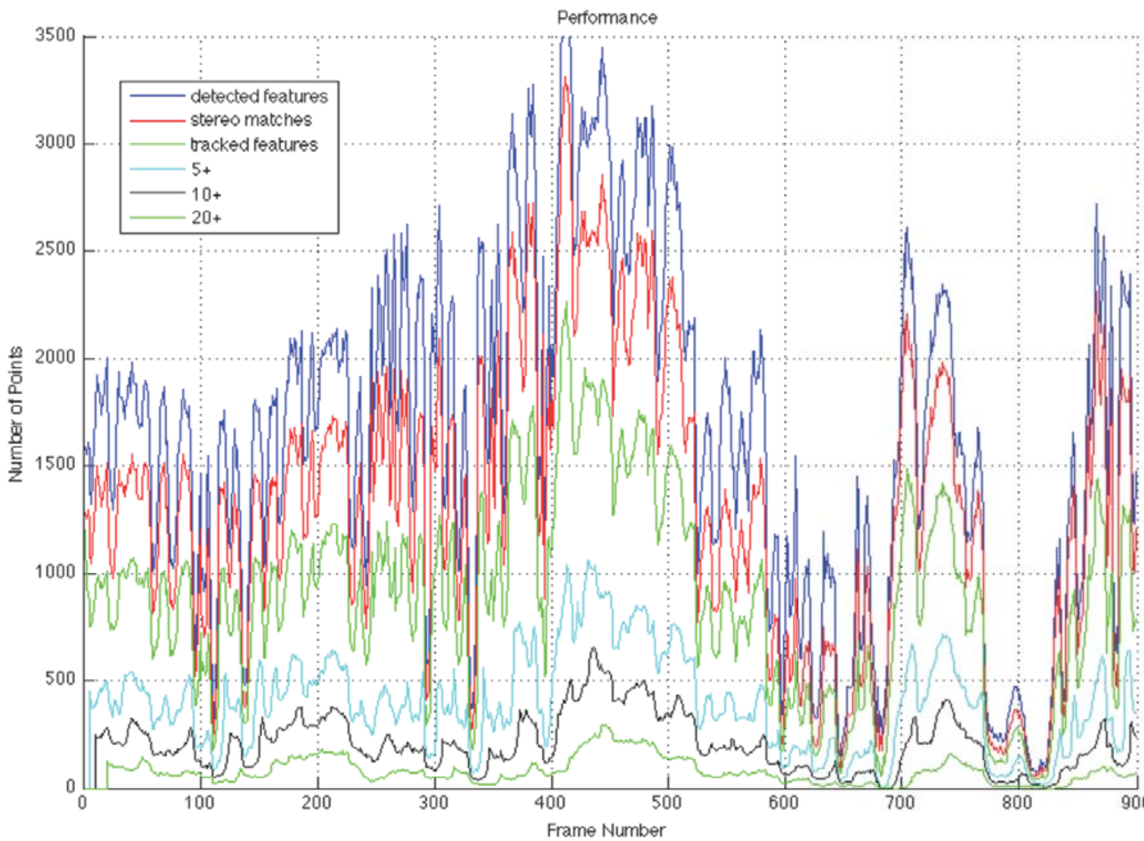


Figure 4: Visual odometry feature detection and tracking performance. From top to bottom, the graph shows the number of features detected in the left frame, the number of stereo matches, and the number of features which were tracked for at least one, 5, 10, and 20 frames.

As discussed in the activities document, Chris Beall examined bio-inspired visual odometry techniques as one step in a larger pipeline to create detailed underwater 3d models. Accurate, full camera trajectories are needed to serve as the basis for dense 3D reconstruction, which is the ideal foundation on which to base subsequent dense reconstruction algorithms. The data was collected as synchronized high definition videos collected using a wide baseline stereo rig. We experimented with a number of data collection methods, including hand-held, attached to a boat, and mimicking the conditions of an autonomous underwater vehicle.

All this was described in a 1010 IROS paper, “3D Reconstruction of Underwater Structures”, with Viorela Ila, a postdoctoral visitor in our group. Figure 4 shows results from the robust feature detection and stereo matching steps implemented by

Chris. To deal with scale and affine distortions in SIFT, for example, keypoint patches are selected from difference-of-Gaussian images at various scales, for which the dominant gradient orientation and scale are stored. Our technique produces similar results whether we use SIFT or SURF, with SURF running significantly faster. The results in the IROS paper were generated using only SURF features. Given the SURF features, we established matches between left and right images in the usual manner. At each iteration, features are matched temporally by individually comparing each feature descriptor from the current pair of images to the feature descriptors in the previous pair of images, restricted to a small search region within the previous image. The incremental rotation R and translation t which express the current frame's camera pose with respect to the previous one are recovered by way of applying a three point algorithm within a RANSAC framework.

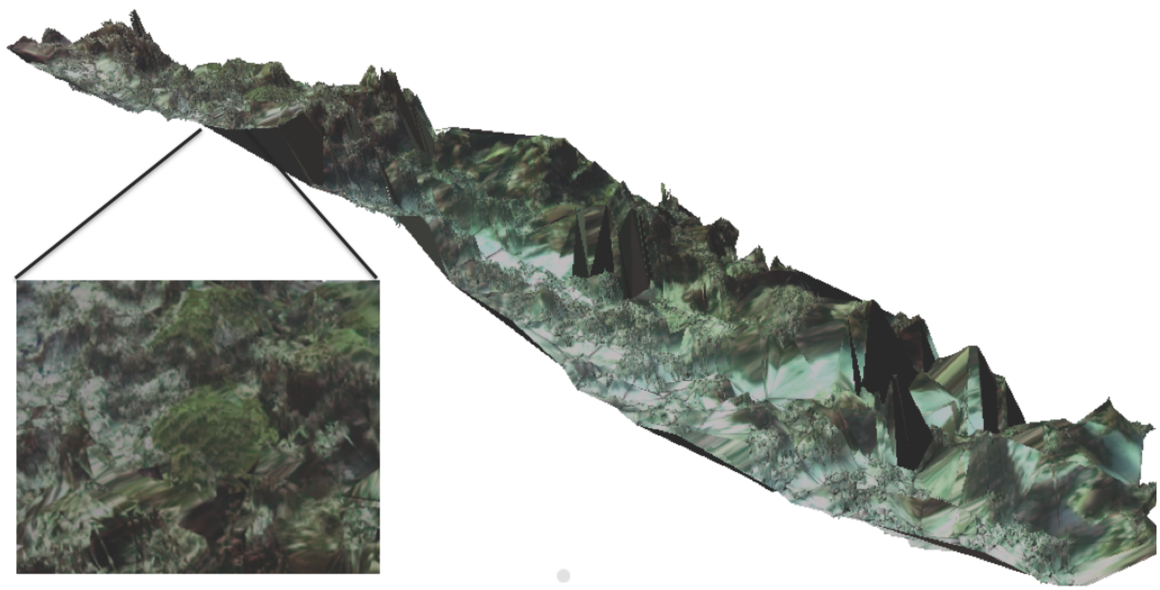


Figure 5: 3D reconstruction of coral consisting of 670 camera poses and 47 thousand faces.

Composing the incremental rotation and translation for each new stereo rig pose with the previous stereo rig pose yields a camera trajectory in the global coordinate frame. Putative inliers are saved to be used for batch smoothing and mapping in the following stage. We solve this problem by employing a smoothing and mapping toolkit developed in our lab specifically for this type of application. The result of our technique is a highly accurate sparse 3D reconstruction of underwater structures such as coral reefs, shown in Figure 5.

Figure 6: Sirius AUV trajectory (in orange) and ocean floor point cloud (of a sunken coral reef) with the 3D point colors taken from the corresponding underwater images.

Chris also published a paper in Oceans 2011, on data obtained via a collaboration with Australian Centre for Field Robotics, in University of Sydney, Australia. The data used for this work was collected using the Autonomous Underwater Vehicle Sirius, equipped with a suite of oceanography sensors, as well as a stereo-camera, multi-beam sonar, doppler-velocity log, and a GPS that can be used to geo-reference underwater surveys when the vehicle surfaces. The AUV is passively stable in pitch and roll, meaning that the stereo rig mounted in the bottom compartment is always imaging the sea floor. The stereo camera pair has a baseline of approximately 7 cm and a resolution of 1360x1024. Data was collected at the South Scott Reef, which is located 300 km northwest of Cape Leveque, Western Australia. The survey covered an area of 50m times 75m , and consists of 9831 stereo image pairs, taken at a frequency of about 1Hz, with the AUV programmed to maintain an altitude of 2m. The AUV was programmed to follow a predetermined trajectory in the survey area. The spatial overlap in between temporally consecutive images generally is around 50%. Images collected by the stereo camera are preprocessed to compensate for lighting and wavelength-dependent color absorption of the water.

Chris showed that smoothing and mapping leads to 3D maps that are more consistent than those resulting from employing a filtering approach, due to optimizing over all cameras and landmarks, and does not suffer from the incorporation of linearization errors as do filters. Figure 6 shows the result.

Final Report: Bio-Inspired Navigation

Activities

Academic Year 2007-2008

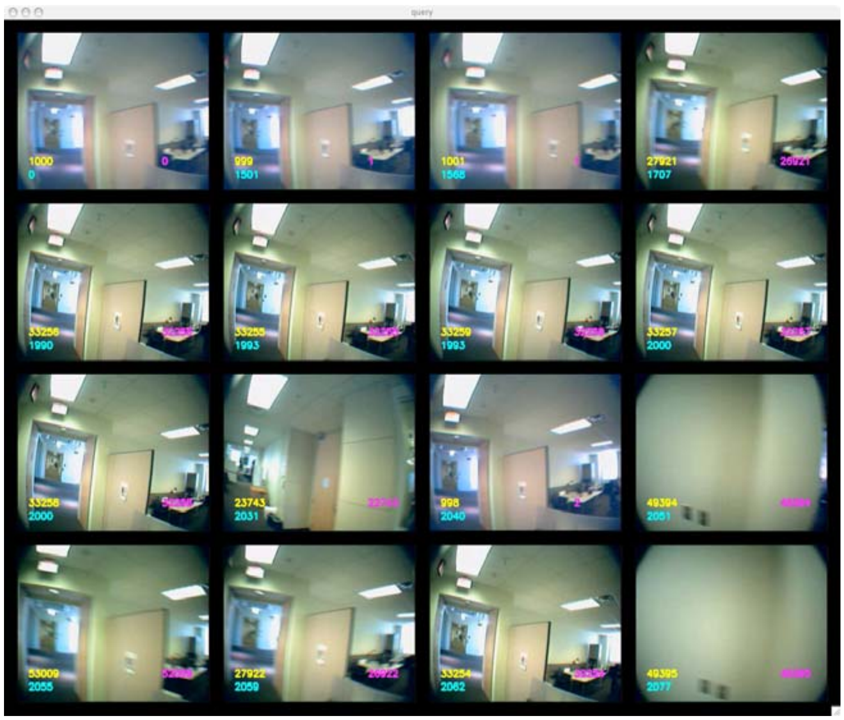


Figure 1: Some of the 60K images acquired by walking around in the Technology Square Research Building, to investigate memory-based navigation strategies.

A key component of the proposed research is the concept of navigation via *topological maps*, graphical representations of the environment consisting of nodes that denote landmarks, and edges that represent the connectivity between the landmarks. Automatic detection of landmarks, usually special places in the environment such as gateways, in a general, sensor-independent manner has proven to be a difficult task.

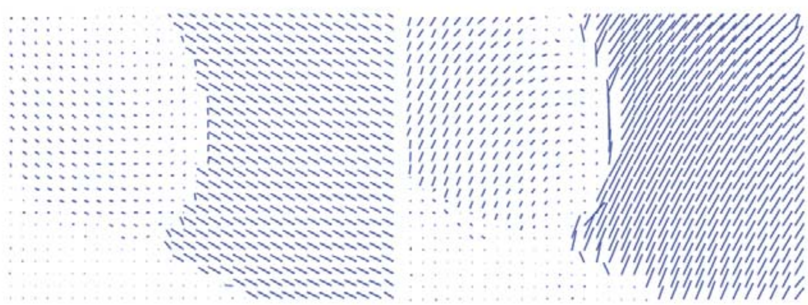
In Fall 2007, **Ananth Ranganathan** and the PI worked on a landmark detection scheme based on the notion of "surprise" that addresses these issues. The surprise associated with a measurement is defined as the change in the current model upon updating it using the measurement.

In the spring of 2008, Ananth finished his PhD dissertation and successfully defended it. His committee consisted of the PI, Prof Frank Dellaert, Professors Balch, Christensen, and Rehg from the Georgia Institute of Technology, and Prof. Ben Kuipers from the University of Texas at Austin. After graduation, Ananth took a research scientists position at Honda Research, in Cambridge, MA, to work on the Honda Asimo humanoid robot.

In the summer of 2008, the PI worked with a M.Sc. student, **Tarandeep Gill**, on image- based place recognition. In particular, we have investigated the use of random projection methods to speed up and simplify the lookup of similar images in a large database of up to 60,000 previously acquired views (See Figure 1).

Academic Year 2008-2009

(a) Typical "ad-hoc catadioptic" frame



(b) Basis flow 1 (c) Basis flow 2

Figure 2: Richard Roberts worked on a bio-inspired optical flow paradigm, where a camera system with arbitrary optics (here including a mirror, as shown in (a) above) is moved through the world (here using rotation only) and we can learn "basis" flows corresponding to each DOF of movement (Figues (b) abd (c) above, corresponding to two degrees of freedom).

This work was continued in the Fall of 2008 in the form of an independent research project, in which Tarandeep systematically investigated the performance of different nearest neighbor pre-processing schemes including random projection (of various dimensions), principal component analysis, and severe down-sampling of the images a la Torralba et al.

Also in Fall 2008 the PI started working with a new incoming student, **Alireza Fathi**, funded by the award, on a biologically inspired SLAM method called EasySLAM. The idea is to use allocentric reference views available in the environment to build local maps, consisting of allocentric links to other maps nearby. By not trying to fuse odometric information (except to serve as an initial estimate for position) the SLAM optimization process decouples and the method is eminently scalable: every location in the world is associated with a "mini" local map, and a graph built on top of these many maps provides a topological map useful for navigation. This was explored independently of image processing problems by augmenting the environment with AR-toolkit markers, which could then be used by the robot to recognize places.

Finally, the PI also brought in a new, currently unfunded student, **Richard Roberts**, to investigate novel bio-inspired optical-flow based methods for navigation and egomotion estimation. This work was very successful, and the PI decided to start supporting Richard from the award in the Fall of 2009. His work on bio-inspired optical flow methods was accepted to CVPR as an oral presentation, an acceptance rate of only 4%. This he then presented at CVPR in the summer of 2009, in Miami.

Academic Year 2009-2010

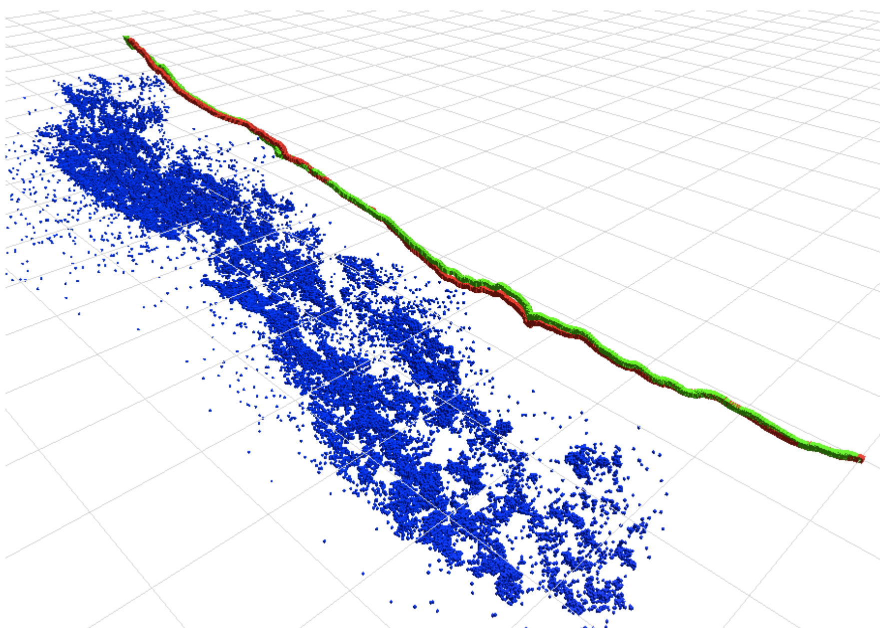


Figure 3: Chris Beall investigated stereo-based "Visual Odometry" in underwater settings. Above is a 3D reconstruction obtained after VO of a coral reef, re-constructed from data acquired on Andros island. Chris investigated several bio-inspired schemes to improve the VO performance, including low-resolution image-based pre-registration to obtain the rotation *R*.

In Fall 2009, after an internship at Microsoft Research, **Richard Roberts** started work on the project. Inspired by this work, Richard and the PI started looking more closely at bio-inspired methods for using not just flow but also the entire joint image to perform localization. In particular, we investigated "Appearance Manifolds" based on a more general idea called "chart-based mixture models", a generative joint probability density model on image measurements and the underlying latent variable from which they arise, specifically for the case where the latent variable lives on a differentiable manifold. The key contribution is that we do not assume that the latent variable manifold is globally isometric to a vector space. That is, there is no natural global coordinate system nor origin for the latent variable manifold.

Instead, we exploit the differentiable manifold nature of the latent variable space as encoded in a chart atlas.

In Spring 2010 The PI funded two GRA students, **Richard Roberts** and **Chris Beall**. After the appearance manifold idea did not pan out as planned, Richard started work on implementing some of the bio-inspired optical flow ideas on aerial platforms. For micro- aerial vehicles, using computationally efficient bio-inspired methods makes even more sense than for ground vehicles, which after all have the ability to carry more power and computation, two things that are severely constrained on small flying platforms. Richard implemented two algorithms on two different platforms. The optical flow work from CVPR on a small coaxial helicopter at GTRI (the Georgia Tech Research Institute, Georgia Tech's contract research arm), and a view-based SLAM method on another coaxial helicopter in the school of Aerospace Engineering at the Georgia Institute of Technology.

Chris Beall, who had previously worked on visual odometry, was brought into the project as a GRA and continued work on implementing stereo visual odometry for underwater scenes. This completes the full realm of environments in which we are testing our algorithms: on the ground, aerial, and underwater. Chris worked on data that we collected on Andros Island with funding from the GVU center at Georgia Tech, with the intent of reconstructing coral reefs (See Figure 3). The coral reef underwater environment is very rich in features, and the data was captured with high-res video cameras, so a lot of Chris' effort went into revising previously developed biologically inspired visual odometry methods to deal with this challenging data. Chris investigated several bio-inspired schemes to improve the VO performance, including low-resolution image-based pre-registration to obtain the rotation *R*, with the intent of improving the speed and quality of VO.

Academic Year 2010-2011 (No Cost Extension)

Figure 4: Camera-equipped diving mask used to gather underwater image streams by several snorklers, with the intent of puzzling them together based on appearance matches.

In Summer 2010 the PI visited ETH Zurich for a month, partially supported by this award, where he worked and interacted with members from Prof. Marc Pollefeys' lab, as will as with Prof. Roland Siegwart. One of the ideas discussed was collaborative stereo on flying platforms: how can two autonomous aerial vehicles, both equipped with a monocular camera, create a "fluid" stereo rig? Particularly the question of observability was seen as central: can the continuously changing baseline be deduced from the monocular camera streams fused with the two inertial measurement units (IMUs) on both platforms?

In Fall 2010 both **Chris Beall** and a new student, **Yong-Dian Jian**, were supported on the award, although Chris only for a very small amount as he accepted a TA position in the ECE department for Fall, as well. Chris continued to work on stereo VO, including on new underwater data that was obtained over the summer on a trip to Miami with several students in the lab, using camera-equipped diving masks acquired by the PI. One of the main research questions Chris wanted to investigate was whether several monocular video streams can be "puzzled" together (Figure 4). He investigated vocabulary tree approaches as pioneered by Nister (in CVPR 2004), and used in FabMap (Cummings and Newman, at ICRA 2007 and 2008)

With Yong-Dian the PI started exploring a novel idea for visual navigation, albeit less bio-inspired than the other threads under this grant: the use of pre-conditioning for structure from motion. While pre-conditioning is typically used to speed up batch-optimization and/or bundle adjustment, the PI felt there was good potential for work based on this to extend to on-line, real-time navigation methods as well, especially when coupled with the PI's earlier work on incremental direct methods. Yong-Dian focused on applying the idea of subgraph preconditioning to structure from motion and visual SLAM.

In Spring 2011 Chris Beall focused on using the underwater VO results to support large-scale underwater reconstruction methods, working with data obtained from new collaborators, ACFR in Sydney, who had previously acquired very large-scale survey data on sunken reefs near the great barrier reef.